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A SYSTEMS APPROACH TOWARDS HIGH ENERGY LASER IMPLEMENTATION ABOARD NAVY SHIPS

by

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June 2007

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The next generation of naval surface vessels will feature a weapon system with pinpoint accuracy, deep magazines, lower cost per kill shot ratio (~ price of fuel), and delivery at the speed of light, this transformational weapon system will provide significant advantages over the conventional systems of today. The Free Electron Laser maintains the greatest potential to become the Navy's first line of shipboard defense and possible a major component in the National Missile Defense Shield, this is possible because the Free Electron Laser will in theory be capable of scaling high power levels to that of the megawatt class which is considered the threshold for military application. The focus of this thesis was to study the implementation of this directed energy weapon from a systems perspective and to determine if such implementation is plausibly possible within the constraints of a naval platform. This thesis will discuss the components of implementation such as the electric drive, integrated power system, pointer-tracker system, etc., which are vital to the total ship weapon package.

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

AA	Anti-Air
ABL	Airborne Laser
AIM	Advanced Induction Motor
AOR	Area of Responsibility
ARMS	Aerospace Relay Mirror System
ASCM	Anti-Ship Cruise Missile
ASM	Anti-Ship Missile
BDA	Battle Damage Assessment
CIWS	Close-In Weapons System
CIC	Combat Information Center
CONOPS	Concept of Operations
CW	Continuous Wave
CVN	Aircraft Carrier
CG	Guided Missile Cruiser
C$_4$I	Command, Control, Communications, Computers and Intelligence
DDG/DD	Destroyer
DEW	Directed Energy Weapon
DTE	Detect-To-Engage
EA	Electronic Attack
ESSM	Evolved Sea Sparrow Missile
EW	Electronic Warfare
FCS	Fire Control System
FEL	Free Electron Laser
FELWS	Free Electron Laser Weapon System
GAO	Government Accounting Office
GMVLS	Guided Missile Vertical Launch System
HEL	High Energy Laser
HELSTF	High Energy Laser System Test Facility
HTS	High Temperature Superconductor
IPS	Integrated Power System

IR	Infrared
JLAB	Thomas Jefferson National Accelerator Facilities
LHA/LHD	Amphibious Assault Ships
NSFS	Naval Surface Fire Support
OBT	Optical Beam Transport
PMM	Permanent Magnetic Motor
PTS	Pointer Tracker Subsystem
RAM	Rolling Airframe Missile
ROE	Rules of Engagement
RF	Radio Frequency
SDI	Strategic Defense Initiative
SM	Standard Missile
SRF	Superconducting Radio Frequency
SSL	Solid State Laser
TAO	Tactical Action Officer
TBMD	Theater Ballistic Missile Defense
UCAV	Unmanned Combat Aerial Vehicle
USN	United States Navy
VBSS	Visit, Board, Search, and Seizure
WP	Weapons Posture

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From James:

To my wife, Cynthia, without your patience, love, and support, I would have never gotten this far in my career. I love you more than you'll ever know, because you are my first, my last, my everything and the answer to all my dreams. To my wonderful children, Netaj, Heaven, and Charlena thanks for all the hugs and kisses and providing the most comedy in my life, succeed always and daddy loves you.

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I. INTRODUCTION AND RATIONALE

The ever increasing sophistication of foreign built anti-shipping cruise missile technology poses a great threat to U.S. surface fleet today. Considered the most dangerous of these anti-shipping missiles is the Russian built 3M82 (Moskit M) NATO generically dubbed the SS-N-22 "Sunburn" shown in Figure 1.

The SS-N-22 (Sunburn), Russian built tactical air/surface-to-surface anti-ship cruise missile consists of a 320kg warhead, is capable of Mach 3 at a high-altitude and a sea-skimming low-altitude maximum speed of Mach 2.2, coupled with a maximum effective range of 250km. If the sea skimming mode is chosen, the missile will be first detected by a warship under attack when it emerges over the horizon at a distance of about 15 to 25nm (28 to 45km) or less which would give defenses on the ship about 25-60 seconds of warning time before impact[1]. Anti-shipping cruise missile technology like this significantly reduces the response time of conventional countermeasures intercepts to that of mere seconds depending upon contact weapon release range and ship's conditional threat status. The raw speed of the Moskit makes it a challenging target for shipboard defenses. The People's Republic of China has employed the SS-N-22 on surface ships[2], and it has been rumored that Iran is actively seeking these weapons.

Figure 1. 3M82 (Moskit M). (From: [1])

The rule of thumb in inceptor missile design is: For a missile to intercept a target, it requires 3x the G-force (acceleration due to gravity at sea level, 9.8 m/s^2) of the target

missile. Current shipboard defense measures such as the SM-2 missile and Phalanx Close in Weapon System (CIWS) are reaching the limits of their capabilities to defend against such threats. Directed Energy Weapons (DEW) or commonly named High Energy Lasers (HEL) are now considered to be the next progressive step in naval shipboard defense. Two types of laser systems have been proposed to combat the state of the art missile threat of today and tomorrow. These systems are the Solid State Laser (SSL) and the Free Electron Laser (FEL) systems. For practical purposes this thesis will focus on the integration of the FEL system because the FEL offers greater military application. Also, only the FEL is capable of being scaled in order to produce a megawatt class laser beam at an optimal wavelength capable of operating in a maritime environment.

A. BACKGROUND

Research into the application of laser systems aboard naval ships is not a new concept. Since the 1970's the Navy has experimented in this technology. The first laser systems to be tested for shipboard use were chemical in nature and were subsequently abandoned due to the hazardous byproducts from the system. The chemical lasing medium was expelled in the form of exhaust which proved to be corrosive and highly toxic to ship's personnel and equipment. The system also required large volumes of chemicals which would require a significant portion of ship's space for other shipboard purposes. The research into FEL and SSL systems began in the 1980s with the Strategic Defense Initiative (SDI). Due to cost and little success in the project as well as the fall of the Soviet Union, the government funding into research of FEL was also abandoned only to be kept alive by private research firms and a few colleges and universities around the United States. As of 31 Oct 2006, Dr. George Neil of the Thomas Jefferson National Accelerator Facility (JLAB) introduced to the Directed Energy Professionals Symposium that the worlds most powerful FEL had made a breakthrough by producing a 14.2 kW laser beam at the infrared wavelength of 1.61 μm[3].

For purposes of this thesis, the platform chosen for integration is the Navy's next generation destroyer DD1000. The DD1000 was specifically chosen because it will be the first ship class to feature the electric drive system capable of providing the high

energy power output requirements necessary to sustain FEL applications. Though the schematics of the DD1000 are classified, it is assumed that DD1000 will follow the basic design parameters of the current destroyer class vessel.

This thesis will study the effectiveness of a Free Electron Laser as a viable Navy weapon and propose a system that can be installed on the DD1000 next generation destroyer.

Integration of the Free Electron Laser will significantly improve the defensive capability of future naval surface vessels catapulting the U.S. Navy into a new era of defense in depth applications and future offensive area of responsibility (AOR) mission support.

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II. MILITARY WORTH ANALYSIS OF THE FREE ELECTRON LASER

This chapter will provide a basic understanding of the military worth of FEL systems. A general assessment of FEL's capability to provide military advantage to achieve desired loss or degradation in a target engagement target will be discussed.

A. KEY HIGH ENERGY WEAPON ATTRIBUTES

High Energy Lasers, such as the FEL, place a focused spot of light (visible or IR) on a target instead of "throwing matter" at it: the HEL beam delivers energy to a very localized point on the designated target inflicting thermal damage at the surface of the target resulting, in the case of a inbound missile, target destruction beyond the range of residual fragmentation thus minimizing possible collateral damage.

Free Electron Laser integration poses several attributes that maintain a fundamental advantage over kinetic weapon systems; however as with all systems there exist performance advantages and disadvantages. These attributes are as follows:

1. Advantages

- Delivering energy to a target at the speed of light is the ideal response towards long range targets or if quick reaction is needed because the laser system is insensitive to kinematic threats.
- HELs expend stored energy (in the case of the FEL, electrical energy) instead of bullets or missiles. This has important advantages to the ship as a whole. FEL maintains a low cost per shot because the energy used is produced from the ship's electrical/propulsion plant which are limited by the amount of fuel. Since fuel is the main source for the electrical generation, the logistics trail is shortened to that of a standard replenishment at sea. Also, the FEL system once integrated does not require any outside presence resulting in an inexhaustible magazine to combat targets. These deep magazines allow for the removal of certain types of missiles and bullets which lighten the vessel's tonnage, resulting in faster, more fuel efficient ships.

2. Disadvantages

- FEL requires a finite beam dwell time to accumulate damage to a target. This finite beam will determine the target kill-time which will decrease significantly due to closing separation between beam origin point and target, placing more energy on intercept resulting in levels of graduated thermal damage. The FEL system will also allow the user to shoot-while-looking versus the shoot-shoot-look-shoot method employed by kinetic weapon systems.

- The atmospheric propagation path has the most significant effect on the FEL system performance in beam delivery intensity. Atmospheric effects in the maritime environment such as aerosols, scattering, thermal blooming, turbulence and absorption reduce the beam quality and limit the maximum effective range of the weapon; ongoing research is in place to address these complications[4].

B. IDEAL MILITARY FEL WEAPON PARAMETERS OF EFFECTIVENESS AND EFFICIENCY

Figure 2 [5] below illustrates the requirements that need to be associated with achieving the status of military grade in order to be implemented within the next generation of surface ship design.

	Active FEL Systems			FEL Weapon Requirement	Solid State Lasers (SSL)	Chemical Lasers
	JLAB FEL	AES CW	AES Burst			
Power Output	10 kW	> 100 kW	> 1 MW	> 1 MW	~ 100 kW?	> 1 MW
Power Source	Electric	Electric	Electric	Electric	Electric	Chemicals
Engagement Range & Depth of Fire	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Magazine	Deep	Deep	Deep	Deep	Deep	Limited by Toxic Chemical Storage
Logistical Trail	Generator Fuel	Generator Fuel	Generator Fuel	Generator Fuel	Generator Fuel	Chemical Fuel
Waste Heat Removal	“c”	“c”	“c”	“c”	Conduction (<<“c”)	Convection (<<“c”)
Frequency Choice for Optimal Propagation	Yes Continuous	Yes Continuous	Yes Continuous	Yes Selected	No - Fixed Wavelength	No – Fixed Wavelength
SRF Acceleration	Yes	Yes	Yes	Yes		
Current	10 mA	100 mA	1 A	1 A		
Electron Beam Quality	Good	Excellent	Good	Good		
Duty Factor	CW	CW	10%	CW		
Power Scalability	Limited	Good	Good	Weapon-Grade		

Here “c” is the speed of light

SSL can approach some preferred maritime frequencies

Figure 2. Requirements for a weapons grade FEL. (From: [5])

Due to extremely low power conversion efficiency (10 - 20%), the FEL requires an abundant power source in order to achieve the greater than 1MW of power output required to be considered as weapon grade (the suggested power systems are discussed in the next chapter).

To answer why a greater than 1MW class system is required, three elements must be discussed based on the greatest ASCM threat, the Mach 3 SS-N-22 “Sunburn” in sea-skimming mode 10 meters above sea level :

- Horizontal Radar Range determined by the equation R = $4.12(\sqrt{H}+\sqrt{h})$ where R is the horizon range in km, *H* is the height of the detecting sensors in meters, and *h* is the contact altitude in meters. So assuming the height of the laser beam director is 23.5 meters above the waterline, the R would equate to:

$$R = 4.12(\sqrt{23.5}+\sqrt{10}) = 33\text{km}$$

- Contact velocity is determined by the speed of sound at sea level, 343m/s. This means at Mach 3 the SS-N-22 is closing at a average rate of 1000m/s. Taking into consideration the horizontal radar range from above, this indicates approximately 33 sec until impact.
- Beam Intensity should be enough to melt through a missile body during the engagement time so that the missile will disintegrate due to hull fractures from aerodynamic stress. Dr. R.D. McGinnis stated in his December 2000 Naval Postgraduate School PhD dissertation ‘FEL Development for Directed Energy’ that, “Irradiance and fluence on targets through experimentation have shown that a flux density of 10 kW/cm^2 is sufficient to melt typical missile materials in a dwell time of a couple of seconds. Using the power required equation Pr = $F\pi w^2$ we can therefore predict the minimum required laser output power in order to destroy an incoming missile”[6]. The laser flux density on the missile surface should be F =10 kW cm^2 over a radius spot area of 5 cm (*w*), with an engagement dwell time of 3 seconds. This equates to the average power delivered on the missile’s surface is

$$Pr = F\pi w^2 = (10\text{kW/cm}^2)\pi 5^2 = 800\text{kW}$$

It can logically be concluded that during an engagement, the FEL system will have to account for multiple inbound contacts, as an example, four mach class cruise missiles against a FEL with an output power of 2MW; it would require approx 2-3 seconds of lasing per target to destroy the each inbound threat before impact. In this

scenario the FEL would be able to accomplish its mission within seconds of the missile detection. The FEL system takes into consideration the cruise missiles' mach speed, ability to perform high-G maneuvers, and lasing dwell time. These reasons justify the power output of the system being well within the MW class. Note that the previous scenario does not take into account the effects of atmospheric propagation.

C. ATMOSPHERIC PROPAGATION EFFECTS

The ideal analysis of section II.B.1 is degraded by the maritime environment with emphasis on thermal blooming, scattering, and atmospheric absorption. The following effects are commonly discussed when dealing with spaced-based laser communications [7]and more so within the maritime environment, for further the reader is referred to Lambert and Casey's "Laser Communications in Space".

Thermal blooming is a lensing effect that occurs when the laser begins to heat the surrounding environment causing the air molecule to reach an excited state ionizing in the atmosphere which results in the laser losing it focused cohesion and dissipate its energy into the atmosphere.

Scattering is much like thermal blooming in the divergence of the laser's coherent beam primarily due to distance of target.

Absorption is caused by the elements found in the maritime environment such as water vapor, carbon dioxide, ozone, and diatomic oxygen that remove energy from the laser beam due to interaction with the beam through the medium. Specific wavelengths of energy at which the laser can be operated can be absorbed by these elements, reducing the transmitted power to target. But in case of shipboard defense, the process is minimized because of the target closing the beam origin point. Because the FEL is scalable, the frequency spectrum can be adjusted in order to propagate at a light wavelength that is not overly affected by the absorption factors in the maritime environment.

D. MILITARY UTILITY

Military utility of FEL will provide an assessment of the usefulness of a weapon system to the warfighter in real environments.

In the maritime environment, several suggestions have been theorized to negate the atmospheric effects on the beam. Each of the following methods is capable of being performed within modifications of the beaming system: (discussions from the Ninth Annual Directed Energy Symposium, October 2006 [8]):

Multiple Beam Directors – this method would call for less total energy to be emitted from each beam director thus reducing the heating of the atmosphere which would lessen the effects of thermal blooming. The beams would then need to converge on a single spot on the target and in effect combine their total energy output thus allowing for total energy required to destroy the target to be achieved.

Multiple Targeting Spots – this method would create multiple targeting points on targets to cause disruption within the aerodynamics of the target or even disrupt the target's guidance systems.

Pulse Targeting – instead of a continuous wave (CW) that will dissipate in power on target over range, the pulse method could target the same spot location but fire the laser in burst to prevent scattering and blooming of the beam since a new firing path is used during each pulse.

Each of the presented methods, either separately or in combination, would overcome the disadvantages of the maritime environment.

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III. ELEMENTS OF A FEL WEAPON SYSTEM

As with any weapon system, the FEL is incapable of operating independently from a hierarchy of other critical systems and components. This chapter will chart the path from fuel to system firing, simplifying FEL operation into five distinct segments.

A. THE ELECTRIC DRIVE: PMM VERSUS AIM

Electric-drive technology would change the way that U.S. Navy ships transmit power from their engines to their propellers, as well as the way that they manage and distribute electrical power to both propulsion and non-propulsion systems[9]. The electric drive component is the power source for FEL operation. The Navy has already decided that all future surface vessels will make use of electric drive technology [9], though some of the choices in drive design could be considered to be questionable at best. The Navy's decision as of January 2000 has been to utilize the Advanced Induction Motor (AIM) in the design of future naval ships[10]. However, since then they have shifted to the use of Permanent Magnetic Motors (PMM).

In 1999 the Navy made the initial decision to use the Permanent Magnetic Motor but technical difficulties were encountered which led to the AIM decision. The difficulties in PMM have been corrected since the initial testing in 1999. There are several key factors why the PMM should be considered as the electrical drive system for future naval ship design starting with DD1000: These factors were discussed in a House Armed Services Committee hearing on the "Efficient Propulsion Systems for Navy Vessels"[10].

- Weight – The PMM is significantly lighter than that of the AIM, roughly 70 metric tons of the PMM versus the 200 metric tons of the conventional AIM. To utilize the PMM would allow DD1000 designers to decrease the ships overall displacement which would allow for greater overall speeds and fuel efficiency.
- Power Efficiency – The comparison in overall weight against power generation favors the PMM at reduced power levels where the ship would spend most of its operations.

- Power Generation - Voltage produced by the PMM produces three times the amount of voltage the of AIM. The increased output levels would more than satisfy the energy required by FEL type weapons and still sustain normal ship operations during use of these weapons. Conversely, the AIM also adversely impacts the ship's design because it will require more than three times the amount of cables of PMM, adding to ships displacement.
- Acoustics - PMM is quieter than AIM which is beneficial to ships in mine avoidance and ship acoustical identification from sonar as well not providing any residual harmonics that might have an effect on the FEL beam formation process.

On the horizon for consideration in DD1000 naval application is the High Temperature Superconductor (HTS) motor which is similar to PMM in many aspects. It is being developed in a joint venture between Northrop Grumman and American Superconductor. In theory it will be able to provide 36-39MW of power per unit. The DD1000 configuration calls for two standard units and two smaller 5MW reserve units; this will provide significantly more power output than many of today's surface vessels. The reason HTS motors and generators are so efficient is that HTS wire specifically designed for use in HTS type motors can carry up to 140 times more current than the copper wire of the same size and weight, as illustrated in the Figure 3. [11] More current means greater flux density, more powerful magnetic fields and in the case of motors, more torque per unit mass of the machine. The small strips of HTS wire (shown in Figure 3) carry the same current as the much larger and heavier copper cable.

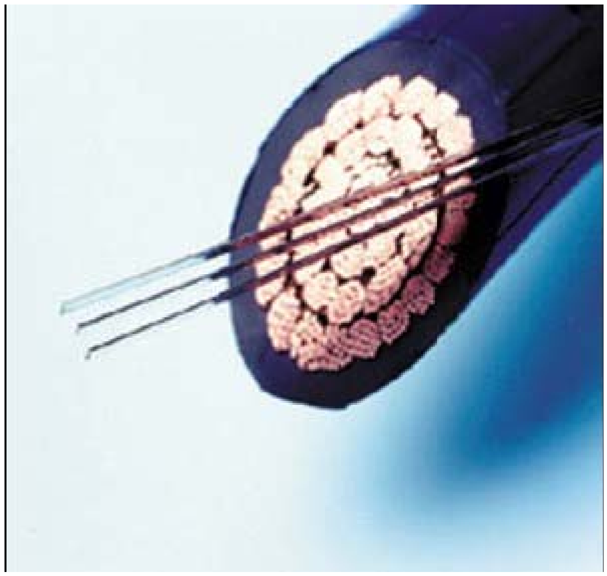

Figure 3. Superconductor. (From: [11])

B. INTEGRATED POWER SYSTEM

The main function of a shipboard Integrated Power System (IPS) will be to mitigate catastrophic risk to shipboard electrical systems in case of cataclysmic damage to various onboard ship systems and to also integrate an advanced electric propulsion system and the ship's electrical services into a single system.

The IPS design allows flexible energy management to match the supply of output power to the tactical environment. For example, the flexibility of IPS energy management will automatically adjust total ship's power to situations which demand maximum top speed such as in torpedo evasion or hot pursuit, when the bulk of the power will be directed for propulsion. While at lower speeds, surplus shipboard power and the energy management flexibility provided by IPS will enable the Navy to field new weapon systems like FEL, high-power microwave systems, and rail guns. The IPS switchboard allows the ships power systems to be use for both propulsion and weapon systems in tandem, even if the ship is traveling at high speed, power can be momentarily diverted

away from the propulsion system to a high power weapon system that requires a short burst of intense power without appreciably slowing the ship down, allowing the ship to maintain maneuverability.

IPS also eliminates the many costly and critical components of conventional propulsion systems. In the case of IPS, instead of the propeller drive shaft being connected to the engine through the main reduction gears which convert the shaft from high speed low torque to low speed high torque, the IPS enables the propeller to be connected directly to an electric motor without the use of reduction gears. As shown in Figures 4 and 5 [12] in contrast to the mechanical drive system, an integrated power system would require fewer prime movers and offer significant architectural flexibility.

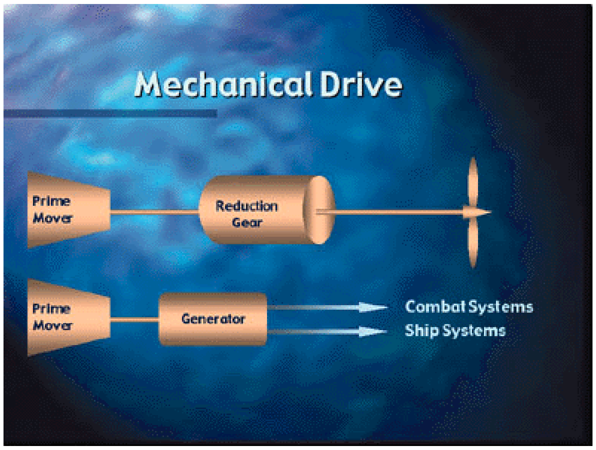

Figure 4. Mechanical Drive Architecture. (From: [12])

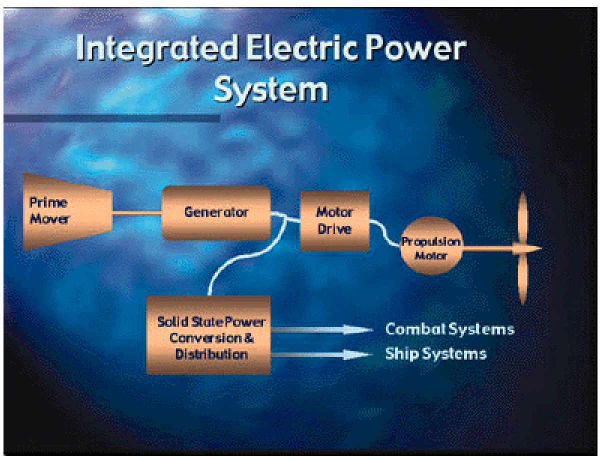

Figure 5. Integrated Power System Architecture. (From: [12])

The IPS will provide total ship power that can be distributed to where it is needed, conserving energy with savings realized through reduced fuel consumption and more efficient engine operating power [12].

C. THE FREE ELECTRON LASER

Figures 6 [13] and 7 [14] represent the design configuration consideration for implementation into U.S. Navy vessels.

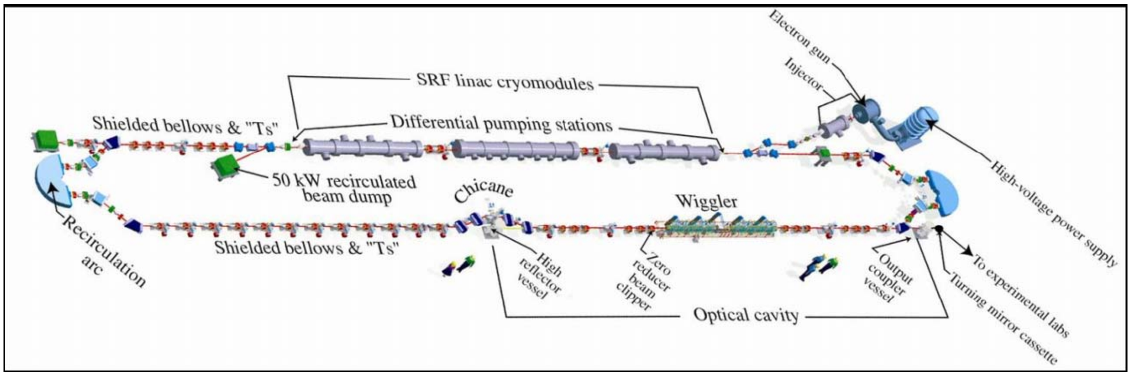

Figure 6. 10kW IR FEL Machine and Component Locations. (From: [13])

Laser classes and types have a wide range of capabilities from chemical, fiber, solid-state to free electron, but of these only the free electron type is capable of operation in the maritime environment due to its ability to scale optical light at various wavelengths for atmospheric propagation.

A recent quote from Dr. George Neil, Principal Scientist, FEL Deputy Program Manager and FEL Facility Manager at The Thomas Jefferson Laboratory National Accelerator Facility in Newport News, VA about the FEL:

> Researchers can "tune" the laser to different wavelengths or color of light, unlike conventional lasers, which emit light at fixed wavelengths and power. The tunability, Neil said, gives researchers the luxury of testing a range of wavelengths and power to find the best settings for a particular task. A weapons-grade laser, for instance, needs a huge amount of power compared with a bar-code scanner……. The tunability of Jefferson Lab's laser has allowed the Navy to test optimum wavelengths for firing a beam

through the atmosphere. That's important because humid air close to the water absorbs many wavelengths of light, which can bend a beam and render it useless [15].

It is able to accomplish its beam cohesion and intensity because unlike other laser types which receive their electrons from a chemical gas-producing compound or a type of crystal, the electrons in the free electron laser are stripped from atoms and then accelerated to achieve higher energy levels. The method by which the FEL produces a high quality energy beam can be found within its components [16]. Further information on the FEL system components can be found at the Jefferson Laboratory website: www.jlab.org/fel.

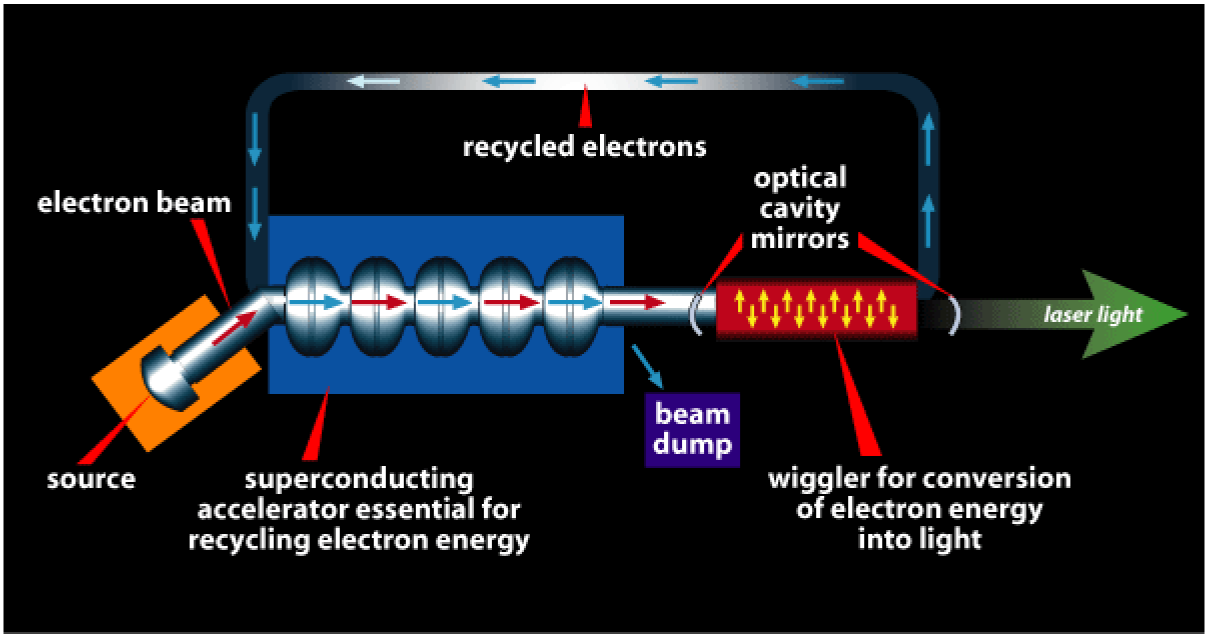

Figure 7. Proposed FEL design for shipboard application. (From: [14])

D. FEL SYSTEM COMPONENTS

The shipboard FEL system will utilize a recirculation configuration which will allow for the electrons to make multiple paths through the Linac and undulator/wiggler allowing the electrons to gain in intensity through the optical cavity. The free electron laser creates an optical beam by feedback that allows operation in the maritime environment.

1. Electron Injector

The electron injector is the origin source of the electrons that are used within the system. Free electrons are produced in a vacuum through either photo or thermal emission from a cathode within the RF cavity.

The electrons will accumulate energy as they pass through each of the injector cells to that of 7-10MeV (shown in Figures 8 [5] and 9 [5]). The electrons leave the injector though specially designed stainless steel pipe called simply enough, the electron beam transport, which is designed to deliver the electron into the Linac while maintaining the vacuum and coping with RF heating produced from the injector. The injector is the key factor in being able to scale current kilowatt level FEL to the anticipated megawatt level baseline for military application.

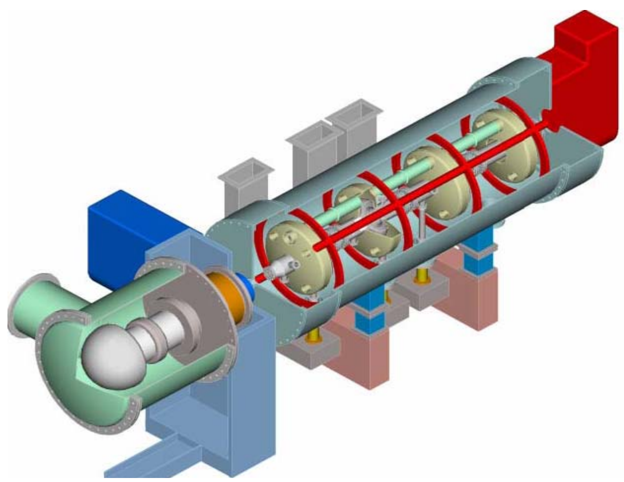

Figure 8. Isometric diagram of the SRF injector. (From: [5])

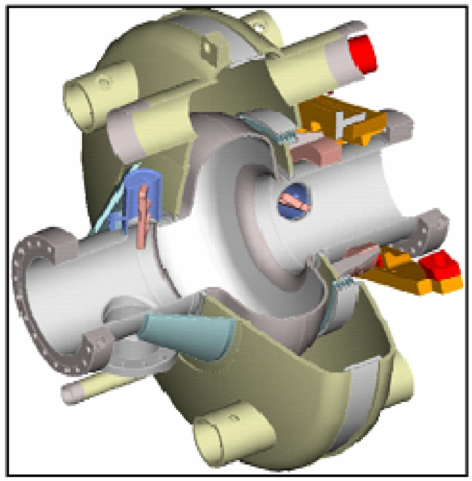

Figure 9. SRF injector cell (From: [5])

2. Superconducting Radio Frequency Linac (SRF Linac)

The SFR Linac (Figure 10) [17] accelerates the 7-10MeV injector-produced electrons to that of 100MeV for the wiggler. It accomplishes this by using standing RF waves in each of the cavities in order to produce an accelerating electric field by which the electrons acquire the additional energy. In the recirculation configuration, energy is conserved because the electrons that have passed through the Linac and undulator are unable to pass freely though the optical cavity and will be recycled back through the Linac where there residual energy is absorbed by new electrons making their first path through the Linac.

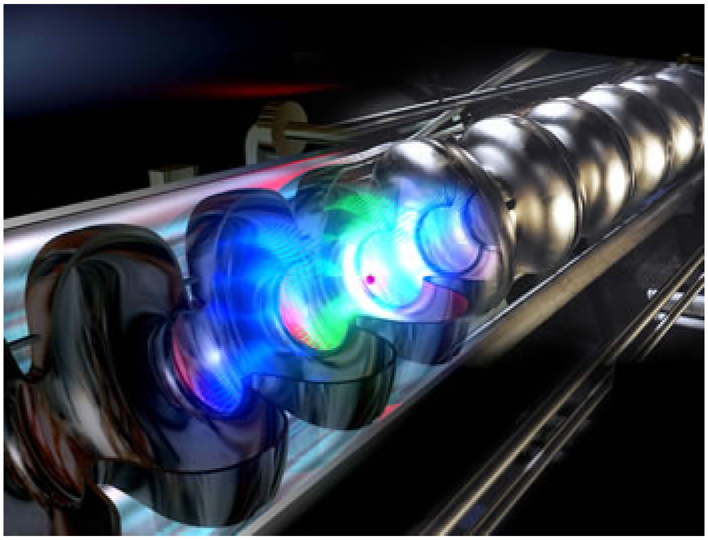

Figure 10. Artist representation of the inner workings of a SRF Linac. (From: [17]

3. Undulator

Commonly referred to as the "wiggler" (shown in Figure 11 [18]), the undulator is a series of alternating polarity permanent magnets that create an electromagnetic field that the electron beam must pass through. As the electrons make their path, the electrons wiggle violently to the point where they give off extra energy in the form of light (photons); this is known as the bremsstrahlung effect (German for "braking radiation"). The passage of a high energy electron through matter (the electromagnetic field) therefore results in the emission of high energy photons that proceed into the optical cavity. The undulator also regulates the frequency of the light waves by means of adjusting the timing (spacing) of the electromagnetic path or by altering the current through the electromagnets.

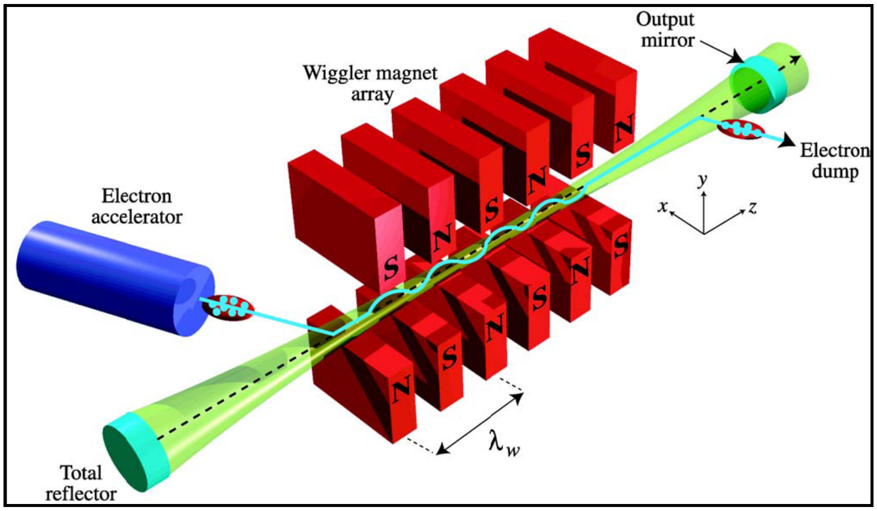

Figure 11. Electron beam path through the undulator and optical cavity, (From: [18]

4. Optical Cavity

As the photons leave the undulator, a mirror reflects the light back through the undulator towards a second mirror; this is called the optical cavity. The first mirror or exit mirror that causes the initial reflection is only 50% transmissive meaning that the light must become more intensive from the multiple reflective passes through the undulator in order to pass through the exit mirror; the second mirror in the optical cavity is 100% reflective. Coherent intensity is created as the discharged photons are reflected back through the undulator and combine with newly created photons to create a coherent beam of high intensity that permeates the exit mirror. This intense coherent light output is the actual free electron laser beam.

Due to the sheer size of the current FEL (240 feet long, 30 feet wide and about 4 feet tall) optimal location of the FEL would be centerline on a deck at the ship's waterline.

5. Optical Beam Transport (OBT)

The Optical Beam Transport will route the FEL beam though the ship towards the beam firing directors. Due to the positioning of the FEL, the OBT will be required to transverse several decks and multiple bulkheads. Much like the electron beam discussed

earlier, the OBT will also operate within a vacuum to prevent any undue loss of beam energy. As the beam enters the OBT a series of reflective mirrors will guide the path of the laser along the center, ensuring the beam does not come into contact with the transport tubing which could distort the beam quality or worse yet, damage the ship. Because of the mirror configurations at splitting points the OBT is capable of providing a FEL beam to more than one director from the same source (without much power loss).

6. Beam Director

The beam director, which is fundamentally a high power telescope, is the actual delivery system and final component of high energy laser system. It is also the component that takes into account the atmospheric propagation and directs targeting of the weapon system. Though often considered as a single component in the laser delivery system, it is comprised of numbers of individual segments to achieve its functionality. To achieve complete 360º horizontal and a vertical range of 190º - 170º, the director must be mounted on a rotating base in conjunction with an optical assembly capable of independent azimuth at a high elevation point on the ship. This high level point of the ship would allow the director to detect and engage contacts at a greater range than lower ship levels and remain unhindered by cut-out points from these lower locations. The best example of a director assembly of this type can be seen on the Air Force Airborne Laser System shown in Figures 12 [19] and 13 [20]. Modified suitably, this beam director would fit seamlessly into the composite design of DD 1000. (The ABL Turret image has been rotated 90º right to give representation of installation on a ship).

Figure 12. The optical ball assembly for the ABL. (From: [19])

Figure 13. The housed turret mounting of the ABL (After: [20])

To ensure target acquisition, the director will have to employ an adaptive optics system that can assist in the firing of the beam through the aberration effect of the atmosphere. (For example, on hot and humid days you can visibility see wave front aberrations in the form of haze; these same atmospheric distortions also affect the beam director as range and power on target are calculated.) As discussed earlier, thermal blooming, scattering, and absorption and turbulence in the atmosphere have a tendency to disperse the effectiveness of the laser's beam on target but these effects also aberrate targeted images to such an extent that the target can be deemed unrecognizable to the weapon system at extreme range. The aberration effect reduces the resolution of the image system by broadening the point spread function within the system. These problems can be corrected by adaptive optics, specifically a closed-loop adaptive optics system. Figures 14 and 15 [21] demonstrate the benefits of adaptive optics. Without adaptive optics the optical beam loses cohesion within the atmosphere. With adaptive optics the system can maintain a greater cohesion which results in increased beam point intensity.

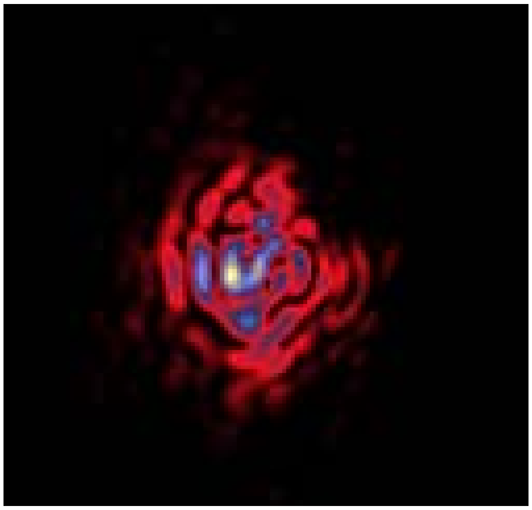

Figure 14. Without adaptive optics. (From: [21])

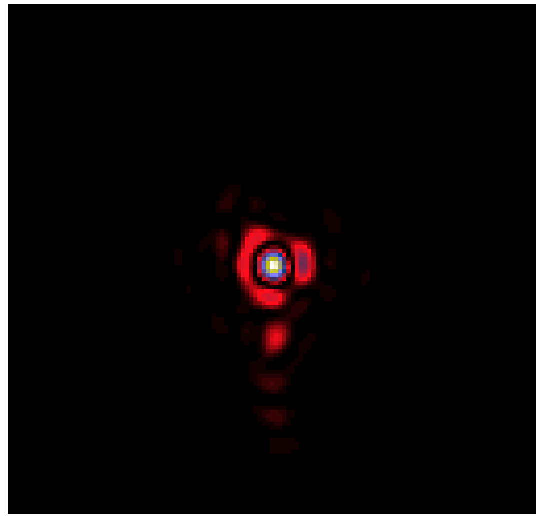

Figure 15. With adaptive optics. (From: [21])

A closed-loop adaptive optics system serves as a corrective measure to distort the optical beam in a manner that is inverse to that of the atmospheric distortions allowing the beam to propagate though the atmospheric distortions and reconstruct accurately at the engagement point. This is accomplished when the detector for sensing atmospheric readings relays these maritime conditions to wave front sensors within the closed loop,;this distortion information is then corrected by sets of deformable mirrors within the closed-loop adaptive optics and transmitted back to the beam director. Deformable mirrors improve optical efficiency of the system by correcting the wave front aberration caused by imperfections in the system components or by the turbulent atmosphere in the case of maritime telescopic optics[22].

Detectors within the director serve the adaptive optics system by providing consistent information on target range, atmospheric conditions and a fixed engagement point. Because of the design of the turret mount, the ball assembly will be able to swivel independently in order to maintain target engagement lock point. A local-loop correction system is used to improve beam quality, and a target loop is used to correct for atmospheric effects. In each loop, distortions in the phase front of the optical wave are measured and corrected by deformable mirrors as shown in Figure 16. [23]

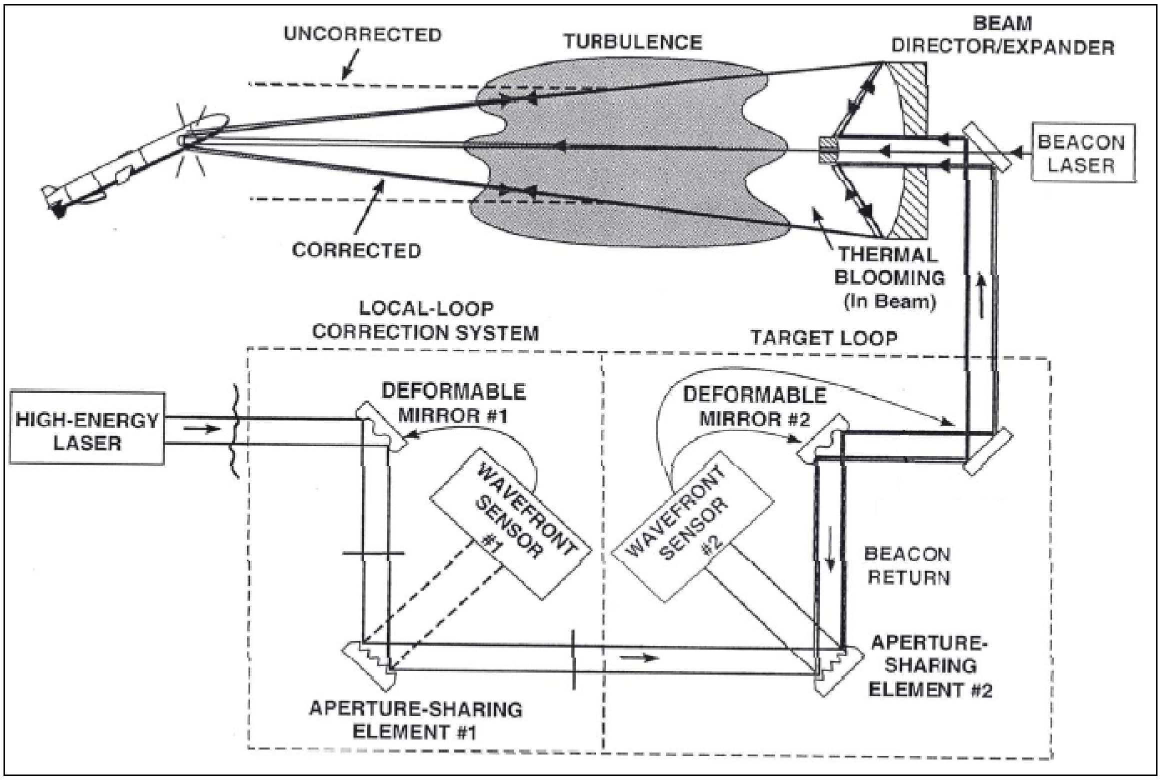

Figure 16. Adaptive Optics. (From: [23])

The ability to control the phase of a propagating optical wave front is a key enabling technology for improving the performance in laser defense applications. By manipulating the wave front, it is possible to correct aberrations in optical systems, control the shape of a focused laser beam, and redirect the laser beam.

7. Auxiliary Equipment

In addition to the electron and optical components of the FEL system, it will require various auxiliary support systems.

1. Liquid Helium Refrigeration system which is used for electron generator and accelerator cooling.
2. Fresh Water cooling for total heat removal from the electronic control systems.

3. Radiation Shielding required to protect personnel from the radiation hazards of the FEL components.
4. Vibration Control systems to mitigate undue system harmonics that affect optical resonance.

These components will not be discussed in detail in this thesis.

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IV. FEL CONCEPT OF OPERATIONS AND INTEGRATION

The development of a MW-class laser weapon system for surface naval platforms will require a new concept of operations (CONOPS) which establishes the core procedures required for baseline system operation. For purposes of this thesis, conops will be discussed from the point-of-view of FEL system integration into the established Ticonderoga Class Cruiser (CG) as reference to DD1000 application. This platform has been chosen mainly because it features the robust AEGIS Weapon System which utilized multiple sensors for not only self defense, but also for the area defense of a carrier or expeditionary strike group.

In addition to FEL module and system integration, command and control aspects as well as a detect-to-engage (DTE) sequence will be discussed. Actual ranges of established weapon systems will not be discussed due to classification of subject matter.

A. FEL MODULE INTEGRATION

The FEL is an encased module that does not require the maintenance and testing procedures that plague kinetic-based weapon systems. Due to the delicate nature of system, calibrations will be set during the testing phase of construction. The system will be integrated into the ship in a manner similar to the engines. Instead of lowering the module from an area near the ships stacks to a position below the waterline, the module will be capable of insertion either vertically or horizontally based on ship design. This should allow Navy ship designers and engineers greater flexibility on the installation of multiple FEL modules.

Because there are essentially no moving parts of the module system, once installed the module storage compartment can be sealed preventing any access that may cause damage to the system. The module will probably require maintenance for upgrades every 5-7 years; this can coincide with the ship's overhaul and depot level repair cycle.

Furthermore, since the integration will complement other system components of the ships kinetic weapon systems, the Free Electron Laser Weapon System (FELWS) will not require specialized training to operate. The operation of the system can be learned as

an additional Aegis weapons course that all Commanding Officers (CO), Tactical Action Officers (TAO) and enlisted Fire Control specialists must take at the Naval Weapon Center in Dahlgren, VA.

B. FEL SYSTEM INTEGRATION

The AEGIS weapons suite is often argued as the best platform for FEL integration because of the AN\SPY-1 radar that is capable of acquiring contacts at ranges exceeding 250nm, but this is a common misconception. Even though the AN\SPY-1 is an exceptional platform, the AN\SPY-1 radar would provide some information required for the FELWS to operate effectively [24]. The FEL integration will require the use of several other sub-systems in order to serve effectively as a defensive component of the AEGIS weapons suite.

The main integration of the FELWS should reside in its being coupled with the AN\SLQ-32 Electronic Warfare System. The AN/SLQ-32 Electronic Warfare System (commonly referred to as ‘slick 32’) is a shipboard missile defense system that provides operational capability for the early warning of hostile weapon system emitters and the emitters associated with targeting platforms and provides the Electronic Attack (EA) capability to alter specific and generic Anti-Ship Cruise Missile (ASCM) trajectories. AN/SLQ-32 maintains a database of many of the world ASCM statistical parameters as well as their various flight profiles. AN\SLQ-32 information significantly enhances the engagement and kill probability of the FELWS and should be considered as the primary sensor system. The AN\SLQ-32 does have a major drawback; it is only capable of providing bearing to target. Though the FEL beam director has the ability to determine ranges to target, it is an inefficient use of this director. To supplement this, the AN\SPG-62 radar component of the MK 99 fire control system (FCS) should be utilized as the secondary sensor system, for it is capable of providing range as well as bearing. The beam director components to determine atmospheric conditions and required power on target should not be utilized until the target is within the edge of optimal efficiency. The information provided from both primary and secondary sources will “handoff” firing of the FEL to the beam director once the target is acquired by the directors’ sensors. The

beam director will automatically train, lock, and engage the target till it registers the contact nullified as shown in Figure 17 ([DDG 1000 from [25]).

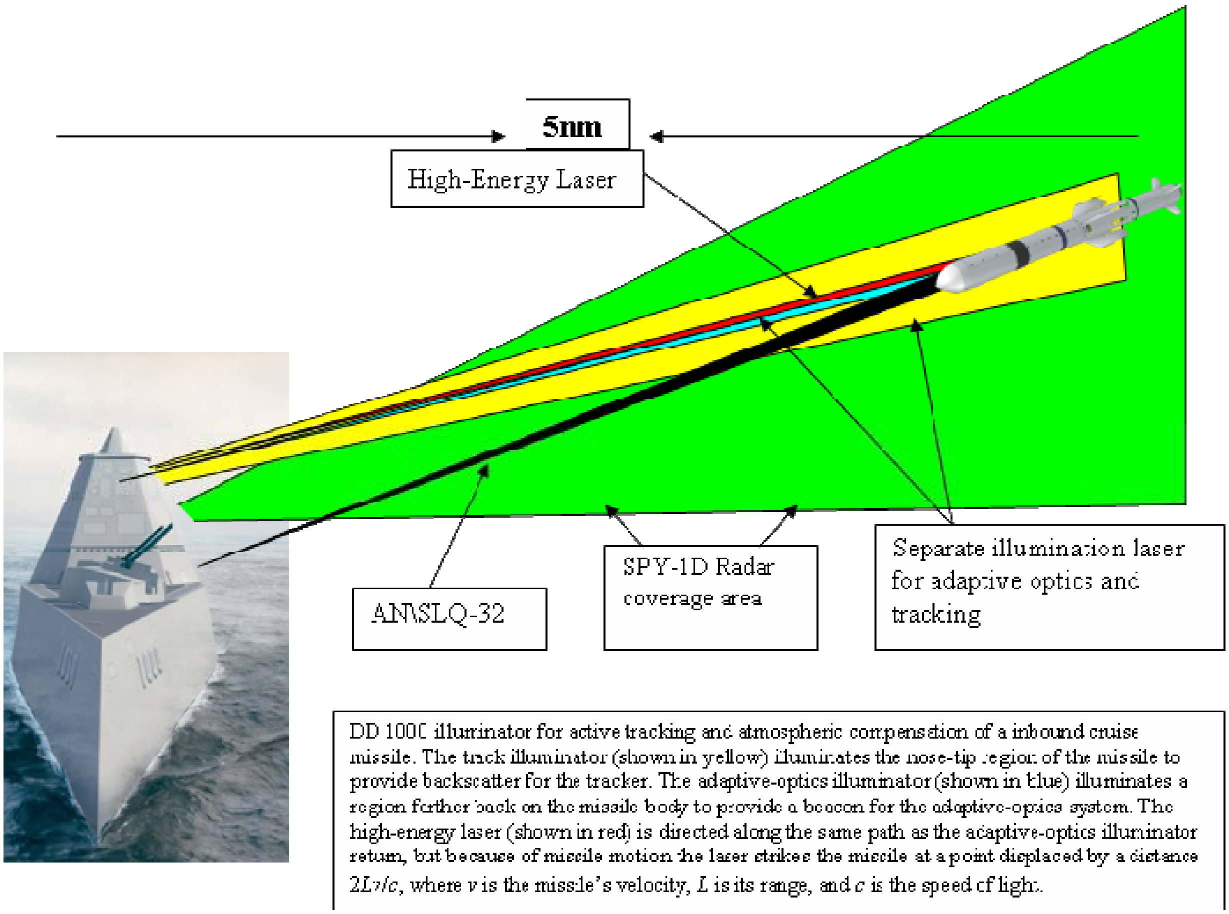

Figure 17. Representation of tracking, identification and firing sensors. (After: [25])

For this thesis, assumptions were made for the use of a single beam director at the ships highest elevation. The design parameters of future naval surface platforms would be sufficient to support the operation of a single FEL system capable of supporting multiple beam directors in various fore/aft, port/starboard configurations.

C. COMMAND AND CONTROL (C^2)

The ultimate achievement of the FELWS integration is to simplify watchstander actions in negotiating threats to the ship. To better exemplify how the FELWS will support the warfighter, the common core command and control procedures of the Close-

In-Weapon-System (CIWS), which is utilized on every surface vessel, will be discussed. Suggestions will be disclosed to modify these actions for FEL integration mainly because FEL will be the prime candidate to replace the current ships self-defense system.

The command and control of all ship's weapon systems will always be the overarching responsibility of the vessel's commanding officer (CO). The CO will often delegate control of these systems to the Combat Information Center (CIC) under the direction of an appointed Tactical Action Officer (TAO). Within the modes of operation, the FELWS should be capable of autonomous detection and engagement of any perceived threat that is programmed into its logic-based software. The FELWS purpose is not to circumvent the hierarchal chain-of-command, but rather provide a tool that will increase the tactical efficiency of the ship's defensive countermeasures. In consideration of the vessel's defensive countermeasures, the weapons posture (WP) capabilities must be addressed. Weapons postures designate a particular weapon system's state of readiness ranging from 4 to 1. WP 4 is normally set when Navy vessels are in-port stateside when systems are taken offline, whereas WP 1 is the weapons system's highest state of alert and is only designated during a hostile action. WP 3 is the normally designated state set during "peacetime steaming", and it is here that some aspects the FELWS should deviate from the ship's normally set parameters [26].

The FELWS is capable of engaging aircraft and surface contacts equally well and as such, tactical control should be retained by the CO and TAO until an assessment of the threat can be determined. The FELWS is capable of operation in both an automatic and manual tactical mode simultaneously. This provides tactical evaluation for the CO and TAO when needed and instantaneous response when the human element is not able to respond as quickly. Since the primary initial targeting data to the FEL beam director is from the AN\SLQ-32, it should be possible to set FELWS weapon posture to 3 for surface and aircraft contacts and WP 1 for ASCM and over-the-shoulder missile threats.

The combination of WPs within the system would allow the capability to rapidly respond to a change in threat assessment. An example of this would be during the assessment of a dhow (a traditional Arab sailing vessel with one or more latent sails) for possible non-compliant Visit, Board, Search, and Seizure (VBSS) inspection. In this

instance, the ship must come within a few hundred yards of the vessel in question. If the vessels operator is armed with a type of over-the-shoulder missile launcher, the Navy vessel would not have sufficient time to engage the inbound missile while the ships weapon systems are in WP 3. If the FELWS is in dual operation mode, the system could instantly identify the threat and take action to destroy it, while leaving the dhow intact to be boarded or even nullified by the manual release of the weapon in surface mode.

D. WEAPONS PAIRING

The implementation of the FEL will not be considered the end-all weapon system from the ship's defensive point of view. The ship will continue to use a combination of naval Standard missiles (e.g., SM2) to engage threats beyond the horizon and the FEL as point defense. The FEL will however allow the ship's defensive countermeasures to be utilized in a manner not before conceived. Instead of the focus being placed on the inbound contact, the TAO can now place more focus on the platform from which the threat originated. This option is now possible because of the destructive force of the FEL on high speed threats. As an example, a U.S. ship is coming under attack from a MiG 27 capable of carrying two high speed anti-shipping missiles with the intent of engaging U.S. forces. The optimal firing range for the MiG 27 is well outside of the engagement parameters of the FEL, but not the 90nm + range of the SM2 missiles. Because there are a limited number of missiles that any one surface vessel can carry, if the MiG releases its payload, under current doctrine the ship will use a minimum of 9 missiles to engage the MiG and its anti-shipping missiles under the shoot-shoot-look-shoot doctrine. The FEL however allows the ship to focus on just the firing platform because the tracking information, bearing and range passed to the FEL will allow the acquisition of the inbound threat outside the optimal firing range of the weapon system. Once the contact is within range, the FEL speed of light engagement will destroy the inbound in 2-4 seconds. This option is possible because the primary task of the FEL system is to automatically engage anti-shipping threats without any human operator interface. FEL control must be a near autonomous weapon system that is capable of higher level threat assessment to properly prioritize engagements to function at peak efficiency.

E. FEL DOCTRINE

FEL doctrine should be constructed\written within a hard code (unchangeable) computer language containing set parameters provided through Naval guidance on ASCM threats. The parameters must provide the system with the definition of a specific operation to determine a successful engagement.

The definition of a successful FEL engagement can be assessed on whether the system deems a soft kill (enabled) or hard kill (destruction) of the inbound is required. Within this set, the FEL can make determination of attack points along the missile frame. A "soft kill" occurs when the FEL is able to target the optical components or seeker components of the missile. The destruction of the missile guidance systems will not destroy the missile rather render it unable to complete its mission.

The "hard kill" will be common in most engagements against cruise missiles. The "hard kill" will result in the destruction of the missile before it is within range to cause any residual damage to the ship. This can be accomplished in typically one of three manners:

- The FEL can target the fuel supply of the missile causing an explosion of the missile frame from the inside.
- The FEL can cut into the missile frame causing aerodynamic stresses to tear the missile apart.
- The FEL can target the explosive payload of the missile, detonating the missile.

These are the most effective means the FEL can employ to engage any anti-shipping missile threat. Every weapon threat poses advantages and disadvantages that can be programmed into the doctrine software suite of the FELWS. These parameters are set forth primarily for the protection of the ship from ASCM threats. Also to be established within the FEL doctrine, if ship's-force requires access, there should be limited access to make modifications within the overarching hierarchy of the system. Threats that call for command evaluation or conflict proportionality are exempt from the programming, thus allowing the CO to determine the level of energy output and duration of lasing during non-missile threat scenarios.

In situations which call for a proportional response or threat evaluation such as a small boat scenario, the CO/TAO would be able to observe any contact through the adaptive optic system featured in the FEL beam director to make a determination of threat. The adaptive optic system operates in the same manner as larger telescopes that are used to peer into the vastness of space. The beam director can be used manually to conduct long range surveillance and identification without generating a beam until deemed necessary. Any proportional response must comply with Geneva Conventions, stated Rules of Engagement (ROE), and international law. Any initial engagement perceived to be a threat or a “hot pursuit” situation, the FEL doctrine must seek to disable the threat vessel as its primary goal. The FEL can accomplish this task by targeting the largest heat source, normally the engine block. Once the vessel is disabled the CO/TAO can confer with higher authority as the perceived threat is rendered vulnerable to U.S. Navy discretion.

The FEL power level can be lowered to provide “warning shots” to craft that enter the ship’s threat perimeter. This lower power setting must be low enough to only cause minor damage such as blistering paint or causing wooden vessels to smolder to encourage the craft to turn outbound or be subjected to U.S. Navy defensive measures.

Rules written with the operating software of FEL provide the ship with greater options to engagement scenarios while eliminating time critical decisions which would put the ship in imminent danger.

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V. CONCLUSIONS AND FUTURE WORK

The future of Navy interest in the FEL will expand from highly maneuverable subsonic\supersonic anti-shipping threats to Intercontinental Ballistic Missiles, anti-satellite warfare and littoral operations through Naval Surface Fire Support (NSFS). Because of the FEL advantages, corporations such as Boeing and Northrop Grumman have already begun to develop various types of HEL relay systems which are still in the early stages of development[27].

A. NAVAL SURFACE FIRE SUPPORT (NSFS)

Naval forces must be capable of sustained offensive and defensive actions against multi-dimensional threats while protecting assured access to sea lanes through power projection and naval presence. To display the projected power of the FEL through other than a line-of-sight means, a tactical relay mirror system must be employed. The mirror relay system is capable of receiving and redirecting the FEL beam in a defilade or enfilade manner to support ground troops. Current designs call for the use of such a relay system to be harnessed on Unmanned Combat Aerial Vehicles (UCAV). These relay systems would allow surgical strike capabilities on the battlefield as well in densely populated urban environments while minimizing collateral damage to ground units.

B. ANTI-SATELLITE WARFARE

FEL can provide naval platforms the ability to render “soft kills” on enemy satellites systems by destroying their optical systems. This provides an enhanced ability for the military in conducting movement and formation of U.S. forces without being tracked from the low-earth orbit. Recent events have indicated that China has been able to “blind” U.S. satellites from a ground-based laser system [28]. The tactical advantage of anti-satellite warfare through use of lasers could prove immeasurable.

C. BALLISTIC MISSILE DEFENSE

Experts agree the most practical method of destroying any ballistic missile threat is to engage the threat in its initial boost phase, preferably while still in the airspace of the

launching country. The speed-of-light engagement of FEL would be practical for launches that occur with the littorals of a country. To engage targets deeper within enemy territory, the Aerospace Relay Mirror System (ARMS) developed by Boeing greatly enhanced this ability. Shown in Figures 18 and 19 [29], when paired with a high-altitude airship the Navy would be able to extend the lethal range of FEL further into hostile territory.

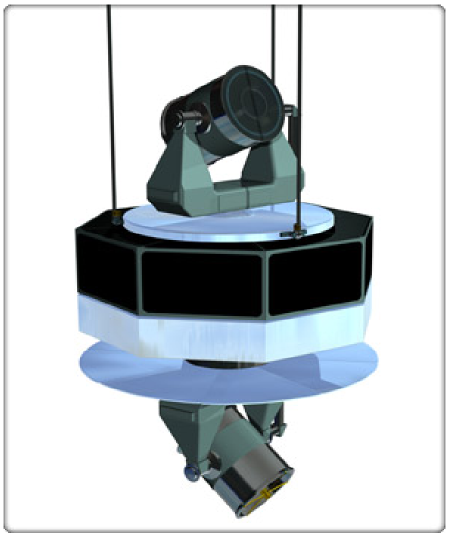

Figure 18. Image of the ARMS. (From: [29])

Figure 19. ARMS extending the range of a laser. (From: [29])

The ship-based FEL could potentially become a key component of a prescribed missile defense shield mainly because the U.S. Navy is always on station.

D. CONCLUSIONS AND RECOMMENDATIONS

The U.S. Navy's next-generation Free Electron Laser Weapon System promises significant tactical advantages over current point defense weapon systems as well as numerous future military applications. By integrating the emergence of the all-electric ship design and the rapid maturing of FEL technology, directed energy can become the key component to the arsenal of the 21st century. The multi-mission capability, controlled lethality, and speed of light delivery offer unique attributes to the Navy and should position the FELWS at the vanguard of shipboard design.

The success of Directed Energy Weapons requires intensive research and development to attain technological maturity for military application. The new capabilities afforded through the use of directed energy technologies will be significant force multipliers because of the numerous improvements to warfare strategies. The use of these weapons offers military strategists an opportunity to select from a range of possible effects to the targeted platform from non-lethal to lethal.

Evaluation based from the research process of current DEW progress, military worth analysis (an assessment of a weapon's ability to provide an accepted military advantage and the associated cost) and application, and technological requirements, the following recommendations, based on June 2001 Department of Defense report on "High Energy Laser Weapon Systems Application [30]", can be made to emphasize the need for a sustained investment funding:

- Atmospheric Propagation and Compensation. Expand the efforts of understanding and correcting of atmospheric effects, especially in tactical maritime environment. Compensation for scintillation effects should be included.
- Modeling and Simulation. Significantly improve the fidelity of modeling and simulation for lasers, beam control, propagation, lethality, and overall system performance. More accurate wave optics models should be developed.
- Adaptive Optics. Start a new technology development program in smaller, lightweight, adaptive optics to allow for smaller beam director aperture and reduce the size of the director assembly to allow for multiple directors.
- Beam Control. Develop low-cost atmospheric sensing components, optical metrology, alignment techniques, and integrate propagation and lethality predictions into the FEL weapon system doctrine. Also, initiate a long-range phasing technique such as phased-array beam control, electronic beam steering, and non-linear phase conjugation in an effort to extend the tactical range of the beam.
- Free-Electron Laser Technology. Focus technology efforts on key elements of the FEL: Scaling FELs to the megawatt class which is required for military applications. Specific investment areas include high average current injectors, electron beam transport, high-power optical resonators, beam expanders, and undulators. Create lighter materials to reduce overall system weight.

Current funding for the research and development of High-Energy Laser systems is estimated to be $100 to $150 million per year for all military services combined. If 10% of allocated costs for kinetic based weapons like Evolved Sea Sparrow Missile (ESSM), Rolling Airframe Missile (RAM), and the Aegis Ballistic Missile Defense (these include SM-3 through SM-6 missiles) were diverted to the advancement of Free Electron Laser technology, this would equate to just under $1 billion dollars annually to HEL programs.

On March 23, 2007 in an article titled “Navy Lacks Plan to Defend Against `Carrier-Destroying' Missile[31]” U.S. Navy officials acknowledge that the Navy is not prepared to defend against Russian built cruise missiles specifically designed to engage U.S. carriers. According to the article, the supersonic missile has been deployed by China and may be purchased by Iran. The Russian designated SS-N-27B (Figure 20) [32], known to the west as the “Sizzler”, starts out flying at subsonic speeds. Within 10 nautical miles of its target, a rocket-propelled warhead separates and accelerates to three times the speed of sound, flying no more than 10 meters (33 feet) above sea level [31].

Figure 20. Image of SS-N-27B “Sizzler” staging area (From: [32])

Table 1 shows the variant capabilities of the SS-N-27B [33]. The deployment of the "Sizzler" could destabilize U.S. naval superiority in critical regions such as the Taiwan Strait or Strait of Hormuz. The article also states that "current and former officials say the Navy has no assurance Aegis, built by Lockheed Martin Corp., is capable of detecting, tracking and intercepting the Sizzler. "

SPECIFICATIONS

	3M-54E	3M-54TE	3M-54E1	3M-54TE1	91RE1	91RE2
Length (m)	8.220	8.916	6,200	8,916	8,000	6,500
Diameter (m)	0.533	0.645	0.533	0.645	0.533	0.533
Weight (kg)	2,300	1,951	1,780	1,505	2,050	1,300
Warhead (kg)	200	200	400	400	76	76
Range (km)	220	220	300	275	50	40
Max speed (Mach)	0.6~0.8; (terminal 3)	0.6~0.8	0.6~0.8	0.6~0.8	0.6~0.8	0.6~0.8
Guidance	Inertial + active radar				Inertial	
Flight profile	Low altitude sea-skimming				Ballistic	

Table 1. SS-N-27B Variant Capabilities. (From: [33])

This ASCM is just the latest in a series of ever more powerful missile threats to the U.S. Navy surface forces and is prime reason that the research and development of Free Electron Laser, as well as other forms of High Energy Laser technology, should be moved to the forefront of weapons research.

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